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Scroll Expander for Carbon Dioxide Cycle

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ABSTRACT

A design has been developed and refined for a scroll energy recovery expander for use in a CO_2 air-conditioning circuit for an 18,000 Btu/hr military environmental control unit (ECU). The design is based on integration of the expander with an established-design two-stage rotary CO_2 compressor. Key technical issues have been addressed through analysis, including bearing loads, friction, leakage, and material stresses and deflections. Testing in a static leakage fixture has been done to verify that refrigerant leakage through the expander, the largest anticipated loss mechanism, is less than initially projected. A proof-of-concept prototype with an internal geometry identical to the expander's design has been fabricated initially for testing in a shaft-output configuration. Initial testing of the prototype has been carried out at off-design conditions. Further testing to quantify the expander performance is ongoing.

1. INTRODUCTION

Interest in CO_2 as a refrigerant has been renewed due to concerns about global warming potential of hydrofluorocarbons (HFCs). Advantages of CO_2 are: it is non-flammable and non-toxic, inexpensive, widely available worldwide from numerous suppliers, and not subject to venting restrictions. The major challenge is to design a cost-effective efficient system that accommodates the unique characteristics of CO_2. Past studies have shown that simple CO_2 cycles for air-conditioning applications theoretically often have lower COPs than cycles based on conventional refrigerants. The CO_2 refrigeration process is generally transcritical, and much of the losses in the cycle are associated with the isenthalpic expansion process which is used in most vapor compression air-conditioning systems. Studies have also shown that the performance of a CO_2 cycle can be improved significantly if energy is recovered during the expansion process, eliminating the performance gap as compared with conventional refrigerants.

Military Environmental Control Units (ECU's) are used all over the world in a wide range of ambient conditions. The design ambient temperature for these units of 125 °F (51.7 °C) is significantly higher than the ambient temperature for Standard ARI Rating Conditions. At higher ambient conditions, the losses associated with the expansion process in a CO_2 cycle are greater, and the potential benefits of energy recovery expansion more important. Our analysis shows that use of an expander is necessary in order to avoid increasing the power requirement as compared with systems using conventional refrigerants, and that scroll technology is well suited to achieving the performance requirements for such an expander.

Previous work (Westphalen and Dieckmann, 2004) led to the development of a scroll expander design and design concepts for integrating the expander with a CO_2 refrigerant compressor. The work has continued with selection of a two-stage rolling piston compressor with which to integrate the expander and development of an integrated compressor/expander design. This paper describes the compressor/expander development, including analysis, design, testing of leakage in a static leakage fixture, and preliminary testing of a shaft-power-output expander for initial evaluation of the design.

2. ANALYSIS TO DEFINE EXPANDER DESIGN PARAMETERS

A two-stage rolling-piston compressor was selected for integration with the expander. Cycle analysis was carried out in order to optimize design specifications of the expander for operation with this compressor. The analysis was carried out for typical military design conditions, including ambient temperature of 125 °F (51.7 °C), and evaporator return air conditions of 90 °F (32.2 °C) dry bulb and 75 °F (23.9 °C) wet bulb temperatures. Key assumptions for the analysis include the following.

- Evaporating Temperature 55 °F (12.8 °C), saturation pressure 699 psia (48.2 bar)
- Gas cooler exit temperature 130 °F (54.4 °C)
- Expander leakage flow 20% of ideal flow, expander overall efficiency 70%
- Evaporator exit superheat 5 °F (2.8 °C)
- Machine speed 3,450 rpm

Performance characteristics of the compressor operating alone without an expander were also used in the analysis. A plot of capacity for the compressor/expander for different high-side pressure levels is shown in Figure 1 below. Based on the modeled characteristics of the compressor/expander pair, a design high-side pressure of 1,800 psia (124 bar) was chosen.

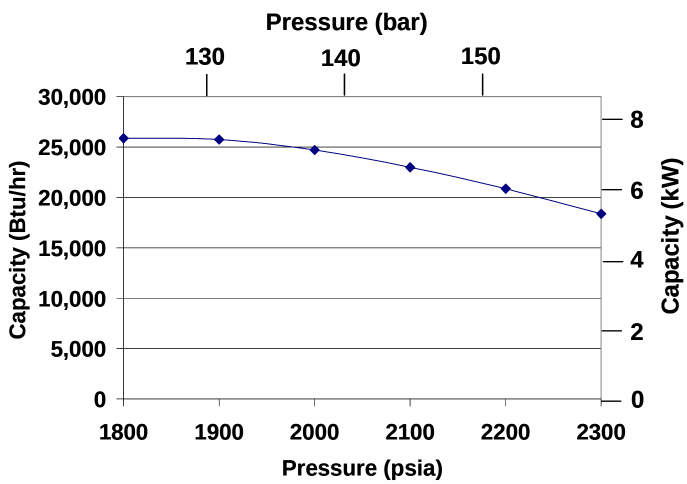


Figure 1: Calculated Capacity vs. High-Side Pressure

Key performance results coming out of the analysis are as follows.

- Use of the expander should raise the capacity from 22.2 to 25.9 kBtu/hr (6.5 to 7.6 kW).
- COP improvement should be about 44%.
- Mass flow 682 lb/hr (310 kg/hr)
- Expander Inlet Volume Flow 579 cubic inches per minute (9,500 cc/min)
- Expander Displacement 0.14 cu in (2.3 cc)
- Ideal Volume Expansion Ratio 2.35
- Design-condition expander shaft power output: 1.5 hp (1,120 W)

A scroll set was designed based on these expander design specifications. The volume ratio was reduced from the ideal 2.35 to 2.0 in order to reduce size. This will reduce the calculated P-V work by a small amount, only about 3%. The scroll wraps fit inside a circle of diameter 2.3 inch (58 mm). Analysis was done to calculate axial, tangential, and radial loads, and the design was adjusted in order to optimize its operating characteristics. Finite element load analysis was carried out in order to assure that stresses and deflections of both the fixed and orbiting scrolls would be within tolerable limits. An iterative progression of weight reduction and stress analysis was done for the orbiting scroll to minimize weight while keeping deflections low. The resulting calculated axial deflection in the center of the orbiting scroll disk was on the order of 0.0002 inch (0.005 mm).

3. VOLUMETRIC EFFICIENCY INVESTIGATION

Testing was done in a static leakage fixture in order to determine the level of through-leakage of the scrolls, since this was projected to be the largest contribution to performance losses. Tests were done with both a cylindrical test fixture and with an actual scroll set. The cylindrical fixture was used previously for leakage testing using nitrogen (Westphalen and Dieckmann, 2004).

A test facility was set up for the expander development which allows testing for the three operational modes anticipated during the project: Leakage testing using static leakage fixtures, operation of a shaft-power-output expander, and operation of an integrated compressor/expander. A schematic of the test facility in leakage testing mode is shown in Figure 2 below. The facility incorporates an entire CO_2 refrigeration circuit and can be reconfigured as needed as project needs evolve.

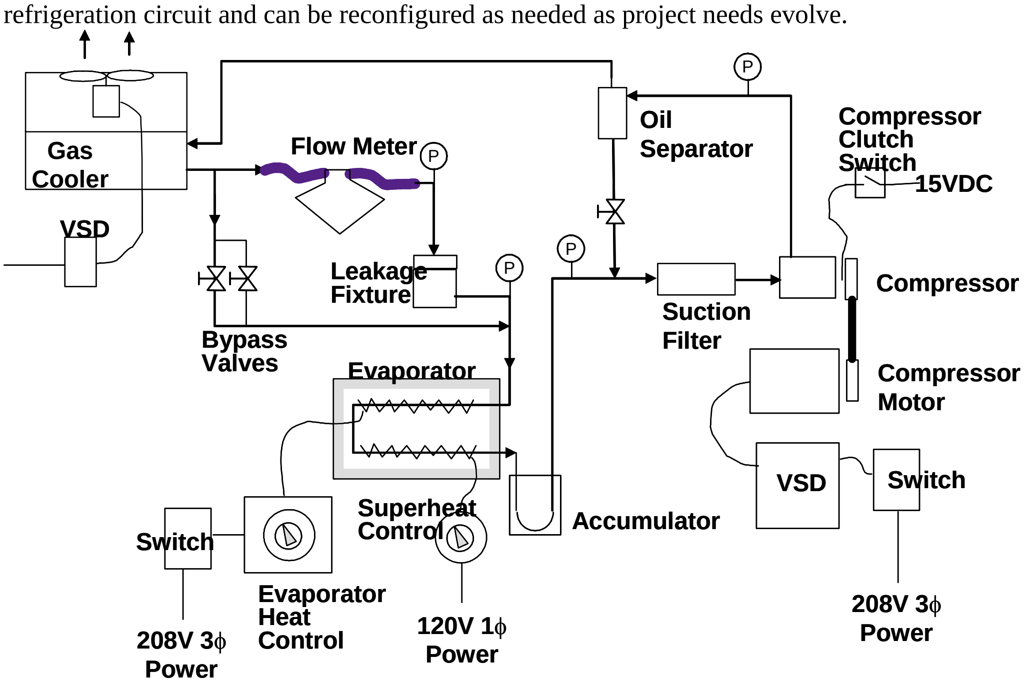


Figure 2: Test Facility Schematic

Testing of leakage using the scroll static fixture using CO_2 is shown in Figure 3 below. This test was done with the scroll at the 335º orbit position, which represents a maximum for leakage path length through the scroll wall tip. Notes to clarify some of this data are as follows.

1. The ~48 lb/hr (22 kg/hr) flow for ~1300 psia (90 bar) occurred very soon after starting flow through the scroll. Experience has shown that flow often starts high and then drops (this may occur because some oil builds up in the gaps to slow down the flow as time goes on). This phenomenon has occurred for both the scroll and cylindrical fixtures.
2. The points plotted are averages of a range indicated by the flowmeter, except that flow was more or less steady for the ~1300 psia (90 bar) points. Maximum observed flow was 67lb/hr (30 kg/hr) for the last point indicated.
3. Expander exit pressure was 465 to 575 psig (32 to 40 bar) for the test set (lower when the expander inlet pressure was higher).

The leakage testing indicates that leakage of CO_2 through the scroll set at design conditions will be close to 60 lb/hr (27 kg/hr) for worst-case leakage gap length. This is less than 10% of the 682 lb/hr (310 kg/hr) compressor/expander design flow rate. Conclusions of the volumetric efficiency testing are as follows. The low leakage is probably due to the presence of undissolved oil in the inlet CO_2 flow, which helps to seal gaps. This oil will also help to reduce friction losses as well. The oil in use in the system for these tests was PAG with an ISO Viscosity Grade of 46 mm^2/s.

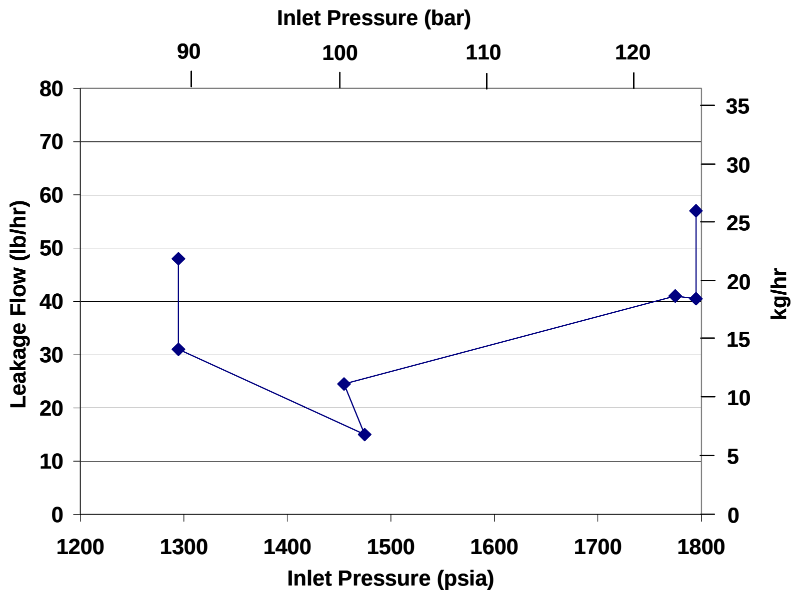
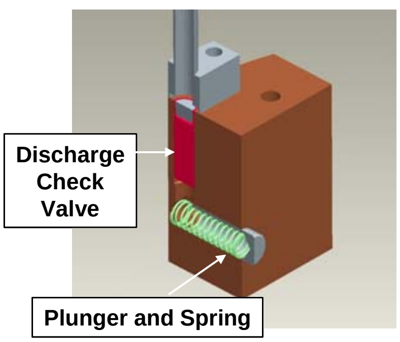


Figure 3: Volumetric Efficiency Testing with Scroll Fixture

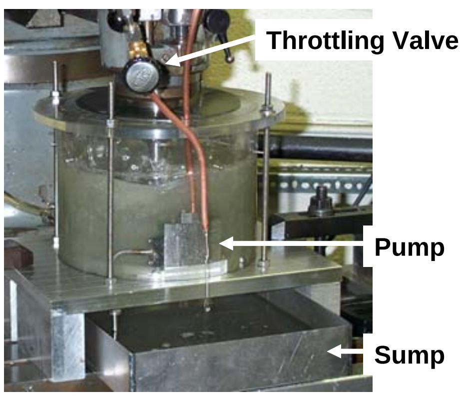
4. INTEGRATED COMPRESSOR/EXPANDER DESIGN

A design was created for the integrated compressor/expander. Key aspects of the design are described as follows.

The scroll expander was located at the bottom of the compressor, to provide power to the shaft through an orbiting drive connected to the bottom of the shaft. Since the established compressor design had an oil pump located at the bottom of the shaft, a new approach to oil pumping had to be developed. A reciprocating piston pump with inlet and outlet check valves was developed for the compressor/expander. The oil pump is mounted at the periphery of the expander, and its plunger is actuated by the orbiting scroll. Testing was done in a benchtop apparatus to verify pump operation. The oil pump design and test are shown in Figure 4 below.



Oil Pump Design



Oil Pump Testing

Figure 4: Reciprocating Oil Pump Design and Testing

Oil supply is routed to the same oil distribution circuits as are used in the existing compressor. Additional oil supply for the scroll's main drive bearing is also provided. The scroll's thrust bearing is provided oil by being located at a height below the sump oil level.

Balance for the integrated compressor/expander is assured through the addition of a main counterweight to balance the orbiting scroll motion. Dynamic balance is assured by adjustment to the compressor motor rotor's trim weight. The counterweight is mounted on the shaft just above the orbiting drive at a minimum distance from the orbiting scroll, thus minimizing the required trim weight adjustment.

Power is delivered from the scroll expander to the shaft through an orbiting drive. The drive is designed with flexibility so that it can adjust to the orbit radius defined by the motion of the orbiting scroll and to adjust for possible deflection of the end of the shaft under the load of the scroll's tangential force. Adjustment of orbit radius provides the radial compliance which assures that the scroll flanks will be in contact, thus assuring good seal of the scroll pockets.

5. PROOF-OF-CONCEPT EXPANDER PROTOTYPE TESTING

A proof-of-concept (POC) expander prototype with shaft power output was fabricated in order to test the scroll performance. The POC interior in the region of the expander was designed to be identical to that of the integrated compressor/expander. The POC included needle roller bearings to support radial shaft loads and a needle roller bearing to support the shaft. A spring-supported polymeric shaft seal is used to prevent CO_2 leakage out the shaft penetration. The test facility was set up with a torque-meter and motor/generator to allow measurement of expander torque output during operation powering the generator. Variable-capacity resistive heaters were connected to the generator output to allow adjustment of the load. Testing was carried out with the same PAG oil as was used for the leakage testing described above.

Initial testing of the POC was successful, demonstrating the viability of the scroll expander. Due to wild fluctuations in the indication of mass flow during the tests, performance of the expander is not fully quantified. We suspect that the fluctuations in this coriolis flow meter are due to changes in density as the amount of oil mixed in the flow varies. Key data for this test are summarized as follows.

- Shaft speed: 3,300 rpm
- Shaft Torque: 14.3 in-lb (1.62 N-m)
- Estimated Torque loss due to shaft seal and supplementary bearings: 2 in-lb (0.23 N-m)
- Calculated shaft power (adjusted for torque loss): 0.85 hp (637 W)
- Inlet Conditions: 1,465 psia (101 bar), 128.5 °F (53.6 °C)
- Exit Pressure: 595 psia (41 bar)

Expander flow for this test appears to have been close to 400 lb/hr (182 kg/hr), but there is a very high uncertainty in this estimate.

6. CONCLUSIONS

A scroll expander design has been developed for integration with a dual-stage rotary compressor for use in CO_2 cooling cycles. The scroll design was based on optimization for military design cooling conditions, in particular for relatively high ambient and evaporator air return conditions. Static leakage testing has been carried out to examine the largest anticipated expander loss mechanisms, that of leakage of CO_2 through the expander. This testing shows that leakage is manageable, being limited to no more than 10% of design expander flow. A shaft-power-output prototype expander was fabricated and testing of this unit has started. Initial testing shows that the unit operates successfully as designed, and quantification of performance is ongoing.

NOMENCLATURE

ECU	Environmental Control Unit	POC	Proof-of-Concept

REFERENCES

Westphalen, D. and J.Dieckmann, 2004, "Scroll Expander for Carbon Dioxide Air Conditioning Cycles", *International Refrigeration and Air Conditioning Conference atPurdue*, July 12-15.

ACKNOWLEDGEMENT

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